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A Review of Leafy Spurge，*Euphorbia esula*（Euphorbiaceae），the Most Aggressive Invasive Alien in North America*

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Abstract：Leafy spurge（*Euphorbia esula* L.，s. lato.）native to Eurasia is one of the most notorious invasive plant in North America. In order to fully understand the current situation well，details of taxonomy，biology，physiology，invasion，damage and loss，as well as various controls of leafy spurge have been reviewed here，and concise prospects and summary are also discussed，with more than 200 references cited as well.

Key words：*Euphorbia esula*；Invasive Plant；North America；Review

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Introduction

Leafy spurge（*Euphorbia esula* L.，s. lato.），a native perennial herb from Eurasia，accident introduced nearly 180 years ago from Europe，has becoming a serious and aggressive invasive alien in the North America，and costs millions and millions of loss，especially in the Northern Great Plains of North America.

In order to fully understand the current situation in dealing with this most aggressive plant in North America，details of taxonomy，biology，physiology，invasion，damage and loss，as well as various controls of leafy spurge have been reviewed in this paper，especially in the past more than twenty years，and concise prospects and summary are also discussed，with more than 200 references cited as well.

Taxonomy and classification

Leafy spurge，*Euphorbia esula* L.（Euphorbiaceae），a native perennial herb to Eurasia，is very variable species in vegetative and floral morphology，and this has caused some problems in the taxonomic field. Taxonomists disagree as to whether leafy spurge should be a single species（*Euphorbia esula* L.，sensu. lato.），or an aggregate of two or more species，not only in Eurasia（Geltman，1998；Ma，1997；Radcliffe-Smith and Tudin，1968），but also in North America（Dunn and Radcliffe-Smith，1980；Biesboer and Koukkari，1992）.

Croizat（1945）treated "*Euphorbia esula*" in North America with four to five species（such as *E. virgata* and many others）. Recently Geltman（1998）discussed the taxonomy，ecology and geography of *Euphorbia esula* L. and *Euphorbia virgata* Waldst.，& Kit. from Europe，and advocated to separate them as different species since the difference of ecological elements.

Dunn and Radcliffe-Smith（1980）used twenty-eight herbaria sheets of leafy spurge from 12 states were examined and compared with European specimens maintained as the Royal Botanical Gardens，Kew，England，and treated five morphologically separable taxa：*E. esula* s. str.，or s. lato（incl. *E. androsaemifolia* Willd.），*E. virgata*（with varieties：*uralensis* & *orientalis*）and *E. x pseudovirgata*. Radcliffe-Smith（1985）made a taxonomic list of 78 taxa under the broad 'leafy spurge' in North America，with many hybrids，

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especially from east and central Europe. His key was with only length difference but nothing reality to be followed or used in practice, even he made full list of most of them in North America.

Ebke and McCarty (1983) collected live root material of leafy spurges (*Euphorbia* spp.) from 38 locations across northern United States, southern Canada and from one location in Austria. These materials were established in a nursery at Lincoln, Nebraska along with *E. agrarian* and *E. cyparissias*. Compared with A. Radcliffe-Smith work, and got five morphologically separable taxa: *E. x pseudovirgata*, *E. esula*, *E. uralensis*, *E. agrarian* and *E. cyparissias*.

Morphometric techniques were used to analyze relationships in leafy spurge and its allies (Crompton *et al.*, 1990). On the basis of studying 26 morphological characters found in 200 collections representing 32 putative taxa, the authors concluded that in North America only four species should be recognized, namely, *E. agrarian* Bied., *E. cyparissias* L., *E. esula* L., and *E. pseudoesula* Schur.

In order to solve the difficult in taxonomic problem (Harvey *et al.*, 1988), the within-plant, within-clone, among-clone, and among-site variation in leafy morphology and triterpenoid content of the latex of leafy spurge were demonstrated qualitatively and quantitatively, and the result shows that latex triterpenoid profiles were useful in distinguishing *E. lucida x salicifolia* and *E. salicifolia* from European *E. esula*, *E. waldsteinii*, and *E. sequieriana* spp. *seguieriana*, and all Montana accessions previously described from morphological studies, and concludes that Montana leafy spurge and the European *E. esula*, *E. waldsteinii*, and *E. sequieriana* belong to a single taxon: *E. esula*.

In short, most scientists from invasive biology field treated and used leafy spurge in North America as *Euphorbia esula* (sensu. lato.), i. e. broad sense, not only from theory but also from practice since it is very hard to separate them. However, other plant names are still used today in the taxonomic field and invasive works.

Distribution and Invasion

The native distribution in Eurasia is very wide and also very common for the most countries in Asia and Europe, from Japan to Portugal, from Pakistan to Sweden, from Russia to Arabian Peninsula. However, it is not aggressive in their homeland since various natural enemies and balanced ecosystem in the nature. It could grow in most of condition both from native and invasive areas in Asia, Europe and North America, especially in mixed prairie, cropland, rangeland, pastures, wildland, open woods, margin of forests, roadside, even un-grazed natural areas, from elevation from sea level to 2 500 to 3 000 m.

In North America, the first specimen collected from Newbury, Massachusetts, USA, in 1827, and it was found from New York as a "rare plant" in 1876, from Michigan in 1881, from Huron County, Ontario in 1889, from Minnesota in 1890, from Iowa in 1899, from North Dakota in 1909, from Manitoba in 1911, from California in 1916, Saskatchewan in 1928, Alberta in 1933, and British Columbia in 1939 (Best *et al.*, 1980). Leafy spurge recognized in at least four states and Canadian provinces in 1913. However, it first labeled as a "weed" in a New York Herald Editorial in 1921, and it has occupied 19 states and several Canadian provinces in North America around 1933. During 1949—1950, it has occurred in all of south provinces in Canada except Newfoundland. In 1970, it occupies 26 states in USA; in 1979, it occupies 30 states; in 1997, it occupies 35 states and south Canadian provinces.

Several further surveys have been made for leafy spurge in North America to determine the extent of the infestations, such as 1930s (Hanson and Rudd, 1933). In 1970s, it is found in

458 counties in 26 states from coast to coast (Reed, 1970; Dunn, 1979), especially it disrupts natural and agroecosystems across much of the Northern Great Plains (Barkosky *et al.*, 2000). In 1992 and 1993, the survey shows that the leafy spurge has been expanded into Iowa′s 26 of 99 counties, and the populations are rapidly expanding especially in the Loess Hills and in the northeastern Iowa (Huerd and Taylor, 1998).

So far, this invasive alien has been reported from 643 counties in 35 States in USA (except southeast USA, north from Oklahoma and Texas to North Carolina, south to Florida, according to the USDA Plant Database, searched at July 10 2007), more than 192 counties and 10 states have been added since the last survey in 1979. In Canada, it is one of ten national principal invasive aliens (White *et al.*, 1993), and widely spread in British Colombia (n to Quesnel, c. 53N), Alberta (n to Fort Saskatchewan, ne suburb of Edmonton; Moss, 1974), Saskatchewan (n to Maidstone, 53.06N), Manitoba (n to Gimli, about 45 mi n of Winnipeg), Ontario (n to near Thunder Bay), Quebec (n to St. Nicholas, Levis Co.), New Brunswick (St. Andrews, Charlotte Co., NBM; Hinds, 1986), Prince Edward Island (York, York Co; Erskine, 1960), and Nova Scotia (North Sydney, Cape Breton Co.; Scoggan, 1978). The record in Henderson Corner, Dawson, from Yukon Territory of Canada, is also reported recently (Cody, 1996).

However, no definite time of the leafy spurge was introduced into North America in the history. Britton (1921) stated that about one hundred years ago, possibly even earlier, the leafy spurge, native of Europe, obtained a foothold in Essex County, MA; the actual date of its introduction is not definitely known, but a specimen preserved in the Torrey Herbarium of Columbia University, deposited at NYBG, was collected at Newbury, MA, by William Oakes in 1827. And in 1875, it was anther record from Groton, NY, i. e. Cayuga Flora. (Source: Invasive Exotic Plants of Canada Fact Sheet No. 9, June 28, 2007)

By searched the literatures, and through the correspondence, Dunn (1985) concluded the four most probable ways leafy spurge was introduced into North America: 1) as seeds present in the soil of the ballast of cargo ships from Europe in the 1700s and 1800s; 2) in the seed stocks of Mennonite immigrants to the prairie states from Russia in the decade of 1870 to 1880; 3) in smooth bromegrass seed (*Bromis inermis* L.) that seedsmen introduced to Canada and the northern United States from Russian and Hungary forage crops; and 4) probably by Mennonites settling in Minnesota to imported many bushels of oats from Russia that were probably contaminated with leafy spurge seeds (Biesboer & Koukkari, 1992). And two most probable areas of its origin (the Ukraine and the Penza Province in the Volga Valley of Russia) and the two general areas of origin (Russia and Europe) have been determined.

Leafy spurge′s spread and dispersal were mainly caused by human activities (including farming, logging, husbandry, livestock, travel, lodging, even trade, import, seed exchange, as well as immigration), since the seed of leafy spurge can′t be carried by wind, and it also very hard for animals to bring away from parent plants to a far distance, and they could be only reached very limited area after dehiscence from capsule at autumn. The potential carrier, such as mourning doves (*Zenaida macroura* L.; Bakke, 1936), and other animals are very limited (Blockstein *et al.*, 1987; Wald *et al.*, 2005), even some reported that birds, animals and even water could spread the seeds (Messersmith *et al.*, 1985).

Infection and Damage

Leafy spurge becomes a serious economic and ecological treat to the productivity of agricultural and natural areas, especially the cattle, the predominant livestock species on the Great Plain of North America (Halaweish *et al.*, 2002, 2003), and reduces rangeland carrying capacity by competing with desirable forages and causing infested areas to be undesirable to cattle and wildlife (Master and Nissen, 1998). It is estimated the leafy spurge has infested about 1 606 185 acres (650 000 hm^2) in North and South Dakota, Montana, and Wyoming, and estimated annual economic effect of infestations in the four-state area is about \$130 million (Sell *et al.*, 1999).

Potential economic benefits (i. e. gross benefits, not including the cost of biological control) from biological control of leafy spurge in the four states region of Montana, North Dakota, South Dakota and Wyoming are estimated (Bangsund *et al.*, 1999). Biological agents were predicted to control about 65% of the region's leafy spurge infestations, about 1.2 millions acres (497 000 hm^2) by the year 2025. Direct economic impacts from control were estimated to total about \$19.1 million annually, and secondary impacts were estimated at \$39.3 millions, for a total annual economic impact of \$58.4 millions.

A rangeland economics model was developed to estimate the economic impacts of leafy spurge infestation on both ranchers and regional economics in North Dakota (Leistritz *et al.*, 1992). Leafy spurge induced carrying capacity reduction of about 580 000 animal unit months, or enough for 77 000 cows, reduced ranchers' annual net income nearly \$9 million. Ranchers did not spend another \$14 million in input costs, which reduced regional business activity. The regional impacts are about \$75 million in reduced business activity for all sectors. These impacts on rancher incomes and regional economics suggest the potential economic returns of leafy spurge control could be substantial.

A bio-economic model was developed to estimate the economic impacts of leafy spurge on grazing land and wildland in a four states regions (Montana, North Dakota, South Dakota, and Wyoming; Leistritz *et al.*, 2005). Leafy spurge infestation on grazing land was estimated to result in a loss in regional grazing capacity sufficient to support a herd of 90 000 cows. Direct economic impacts on stock growers, landowners, and agribusiness firms were estimated to exceed \$37 millions annually, whereas secondary impacts throughout the regional economy totaled almost \$83 millions. Impacts on wildland were smaller but still substantial. Study results indicated the serious nature of the leafy spurge problem in the northern Great Plains region and helped to justify enhanced control efforts.

Forage production and disappearance were estimated in four density classes of leafy spurge early (Lym and Kirby, 1987). Use of cool- and warm-season graminoids, forbs, and leafy spurge was estimated during the middle and the end of each grazing season. Cattle use 20% and 2% of the herbage in the zero and low density infestations, respectively, by mid-season. Moderate and high density infestation were avoided until the milky latex in leafy spurge disappeared in early fall, and herbage availability in zero and low density infestation declined. Herbage use in moderate and high density infestations increased to an average of 46% by the end of the grazing season compared to 61% in zero and low density infestations. An annual herbage loss of at least 35% occurred in pasture infested with 50% density or more of leafy spurge.

The test shows (Kronberg and Walker, 1993; Kronberg *et al.*, 2006) that since leafy spurge is not generally toxic to the ruminal bacteria, but that microbial activity in the rumen may be responsible for enhancing leafy spurge toxicity to cattle. Sheep grazing is an excellent method for controlling large infestations of leafy spurge (Lacey *et al.*, 1984). Although the sheep will no eradicate the weed, with a good management system, they will keep it from spreading. Sheep grazing as a spurge control tool also has advantages over herbicides: ranchers receive a high return for their investment; environmental hazards are reduced; and spurge can be controlled in inaccessible areas.

Leafy spurge was first observed in North Dakota in 1909, and has spread rapidly since. It is found in all 53 counties of North Dakota in the mid 1980s, and is present on nearly 7 percent of the untilled land in the state (Lym and Messersmith, 1985a). Loss of hay and beet cattle production is estimated at $7 million annually due both to reduced forage production from leafy spurges competition and to cattle avoiding grazing in leafy spurge infested area.

The infection of leafy spurge in Manitoba of Canada was just about 7 413 acres (3 000 hm^2) in 1952, c. 113 669 acres (46 000 hm^2) in 1982, and 133 436 acres (54 000 hm^2) in 1995 (Harris, 2005).

A plant pest as complex and tenacious as leafy spurge, infesting nearly 2.5 million acres (1 011 714 hm^2) in North America, with a conservative 1978 economic impact in the US of $10.5 million, has reached a serious, if not critical level (Noble *et al.*, 1979). The problem is most severe on rangelands, pastures, tree belts, parks, waterways and roadsides. Even on cultivated cropland, where leafy spurge has been controlled, it can reduce crop yields 10% to 100%. Among them, Minnesota has highest infestation at 800 000 acres (c. 323 748 hm^2) followed by North Dakota and Montana with 600 000 and 543 000 acres (242 811 & 219 744 hm^2), respectively. The Canadian problem is estimated to be comparable to Nebraska, where leafy spurge currently infects at least 321 000 aces (129 904 hm^2), 76 of 93 counties, the direct loss in forage value attributed to leafy spurge has been estimated at more than $2 million annually, and estimates of direct and indirect losses exceed $16 million per year (Masters, 2003).

North Dakota legislature emphasized leafy spurge control in the 1981—1983 biennium by appropriating $500 000 for a cost-share program. Also, each county was allowed to increases taxes by 1 mill to be used exclusively for leafy spurge control. The funding was divided 33∶47∶20 between the states, county and landowner, respectively. The 1983 and 1985 legislatures provided additional biennial appropriations of $500 000 and $600 000, respectively, to continue the cost-share program through the 1986—1987 fiscal year (Lym and Messersmith, 1985a).

In Manitoba, leafy spurge is an invasive weed species that threatens an estimated 340 000 acres (137 593 hm^2). The study estimates that the net economic impacts associated with the leafy spurge infestation in Manitoba may be approaching $20 million per year (http://www.brandonu.ca/rdi/LSSG/issues_and_impact.htm, searched at July 13, 2007). The total annual economic impact on pasture land is estimated at $16 million. An estimated 225 000 acres (91 054 hm^2) of grazing land is infested in Manitoba with a potential impact of a reduced herd size of 16 540 head. Leafy spurge costs Manitobans more than $5 million per year in reduced producer income ($1 940 040 per year) and reduced production expenditures ($3 104 044). Potential secondary economic impacts on other business sectors are estimated at $11 million per year. Additionally, land values are potentially reduced by over $30 million. This brings potential property tax implications for owners of croplands. While taxes on infested acres may reduce, other lands will have to make up the lost revenue.

In British Colombia, isolated pockets occur in the Thompson, Cariboo, Boundary, East Kootenay, Nechako, and North Okanagan areas (Powell *et al.*, 1994).

In Saskatchewan, the leafy spurge infects approximately 20 000 acres (c. 8 094 hm^2) of pasture and native prairie in a diagonal belt from North Battleford to Estevan (http://www.agr.gov.sk.ca/

docs/environment/Biocon. asp, Biological Control of Leafy Spurge, Agriculture and Food, Saskatchewan, Canada, searched on July 13, 2007).

Grassland bird populations are declining, and invasive plant species, such as leafy spurge, may be contributing to these declines by alter habitat quality (Scheiman *et al.*, 2003).

Prevention is best control, especially for leafy spurge! Infestations of leafy spurge should be eradicated when the problem is small. It is a mistake to wait until thousands of hectares are infested under the misconception that the weed can be eliminated economically later with herbicides, grazing management or biological control methods. Seed production and seedlings establishment can be prevented with available controls at reasonable application rates and expense, but control, once infested, will requires repeated treatments and/or use of expensive agents (Alley and Messersmith, 1985).

The seeds are dispersed a few feet by dehiscence of the capsule and for longer distances by birds, but man is probably the chief agent for seed dispersal. The seeds along with the following issues should be considered: in the crop seeds, in the hays and other feed fed to the livestock, within the cultural tools, machineries and other equipments. One leafy spurge infestation in South Dakota started at the spot where a grain threshing machine, obtained in Indiana, was unloaded in 1918. Thirty years later the infestation, covered over 600 acres (c. 243 hm^2). Successful establishment of large numbers of leafy spurge seedlings in closed grasslands is unlikely; but when the habitat is disturbed or opened in some way, seedlings emerge and survive. Numerous rangelands sites that have been maintained in good or excellent condition have not been invaded by leafy spurge, even though the weed infested adjacent cultivated land or grassland that was abused by over grazing. Frequently, the first areas of native grassland to be invaded by leafy spurge are those that have been disturbed, such as the mounds around badger holes. This is especially true of earth mounds near rocks on which birds might perch.

Biology

Leafy spurge, a perennial herb, one of the first plants emerges in the early spring, as early as March in most parts of North America. It grows all of seasons, from flowering to fruiting, until deep autumn. The multi-branched inflorescence is from top part of the stems, and flowering from May to September, and fruiting from June to late October or early November. Pollination is mainly by insects, such as bumble bees, honey bees and ants (Fowler, 1983). Each individual plant could produce 10—50 capsules, each with 3 seeds, which will dehiscence after capsule opened at mature.

Reproduction of leafy spurge is mainly from seeds and root systems (Morrow, 1979). However, the aggressive and colonizing ability for the most part can be attributed to the vigorous and extensive growth of long roots, which are also capable of regeneration (Raju, 1985), and containing abundant organic reserves which the nitrogen plays in the over-wintering strategy and regenerative capacity (Cyr and Bewley, 1989). The development of an extensive root system and the ability of roots to produce buds enable leafy spurge to explore new habitats efficiently and to complete with other plants. A single leafy spurge plant, once established, will inhabit an acre in approximately 65 years (Stroh *et al.*, 1990).

Cytological and cytogenetic studies were carried out on populations of leafy spurge and its allies primarily from North America but also from Europe (Stahevitch *et al.*, 1988). The chromosome numbers were determined for 126 samples of *E. esula* , 11 of *E. cyparissias* , 1 of the hybrid (*E. x pseudoesula* Schur) between these two species, and 1 of *E. agrarian* Bieb. All plants of *E. esula* were hexaploid. Of the total, 125 leafy spurge accessions had a chromosome number of $n=30$; 1 of $n=25++$. *E. cyparissias* was primarily tetraploid ($2n=20$), although occasional diploids ($n=10$) were encountered. Tetraploids were fertile; diploids were sterile. The hybrid between two foregoing species had a chromosome number of $n=25$, indicating that the *E. cyparissias* parent was a tetraploid; meiosis in the hybrid was abnormal. *E. agraria* was found to have a gametic number of $n=20$, which is the first chromosome number determination for the species; meiosis was normal. Artificial crosses were made successfully between 31 accessions of leafy spurge. Seed germination of the F1 progeny slightly exceeded that reported for natural populations, and meiosis was normal. Pollen stainability studies carried out on herbarium material. Stainability was 100% for most of the samples studied. Extensive pollen size polymorphism was found. It is suggested that this phenomenon supports the hypothesis that *E. esula* is of allopolyploid origin.

Chromosome number variability and chromosome mosaicism were revealed through cytotaxonomic studies (Schultz-Schaeffer and Gerhardt, 1987, 1989). Evidence from the literature for introgressive hybridization between *E. esula* and *E. cyparissias* as well as between *E. virgata* and *E. esula* was substantiated. Chromosome numbers in *E. esula* were $2n=48$ to 60, in *E. x pseudovirgata* $2n=40$ to 64, and in *E. cyparissias* $2n=36-41$. Composite ideograms of *E. cyparissias* ($2n=4x=40$), *E. esula* ($2n=6x=60$) and *E. x pseudovirgata* ($2n=6x=60$) seem to indicate segmental allopolyploidy at the tetraploid and hexaploid chromosome levels. Based on their usefulness as genome marker chromosomes they indicate a close relationship between *E. esula* and *E. x pseudovirgata* as well as a possible contribution of *E. cyparissias* to the hybrid nature of *E. x pseudovirgata*.

Detail reviews about the biology of leafy spurge could be found in Bakke (1936), Best *et al.* (1980), Galitz (1994) and Messersmith *et al.* (1985).

Physiology

The physiological test shows that the leafy spurge dominance in a grazed plant community by tolerating herbivore more than neighboring plants, not by avoiding herbivore (Olson and Wallander, 1999). The role of mature leaves of leafy spurge in inhibition of root bud growth is also reported (Horvath, 1999). Most large herbivores avoid the invasive weed leafy spurge, however, it has high nutritive value based on traditional measures such as crude protein, fiber, and dry matter disappearance and is consumed by sheep and goats (Roberts and Olson, 1999b) because the material from un-defoliated and previously defoliated leafy spurge shoots, mixed in different proportions with grass hay, adversely affects sheep rumen microbial activity and mass in vitro. Various studies have been conducted to determine the behavior of leafy spurge in an invasive condition in North America (Horvath, 1998). Toxicity in foliar- and soil-treated leafy spurge is also reported (Rusness *et al.*, 1998). Polyamines, austins and organogenesis in leafy spurge is also reported (Davis, 1997). The relationship between underground adventitious buds of leafy spurge and sugars, hormones, and environment is reported (Chao *et al.*, 2006). The season expression patterns and characterization of leafy spurge root storage protein was studied in order to find potential targets for chemical or biological weed control agents (Luster and Farrell, 1996).

Seasonal variation in nitrogen storage reserves in the roots of leafy spurge and responses to decapitation and defoliation (Cyr and Bewley, 1990). Seasonal fluctuations of carbohydrates and nitrogenous components in the roots of the noxious perennial leafy spurge are strongly associated with over-wintering strategy. Amino acids and distinct soluble proteins accumulate during fall and remain at elevated levels throughout winter. The formation of carbohydrate reserves in roots was not significantly affected by decapitation of selective defoliation; however, maximum amino acid and soluble protein contents were markedly reduced. Studies on organogenesis of leafy spurge shows that all parts of leafy seedlings can be regenerated when isolated (Davis and Olson, 1993). The seed dormancy is also reported (Foley, 2004), and the results show that the seed coat-imposed seed dormancy. Various fields about leafy spurge in North America were also tested and reported (Hogan and Manners, 1992).

A known lathyrane ester and a new jatrophane ester have been isolated from seeds of two different stands of North American leafy spurge (Onwukaeme and Rowan, 1992). New macrocyclic diterpenoids was also isolated (Liu *et al.*, 2002). Four new jatrophane diterpenoids, esulatin A & B (Manners and Wong, 1985), D and E (Guenther *et al.*, 1998) have been isolated from the roots, and the dichloromethane extract of the whole, undried plant, respectively. Another jatrophane diterpene, esulone C was also isolated and reported (Manners and Davis, 1987).

Cultural control

The strictest definition of the term "cultural control" includes practices that can be used on cultivated land. This limits the control practices to preventive measures, intensive cultivation, competitive crops, or a combination of the three. A broad definition allows use of all nonchemical control practices including grazing livestock and mowing. However, the most practical control measures for use on large infestations on cultivated land include combinations of cultivation, competitive crops and chemicals (Derscheid *et al.*, 1985).

Artificial defoliation was conducted once or twice annually at various phonological growth states of leafy spurge to simulate grazing by herded Angora goats (Kirby *et al.*, 1997). Single defoliation treatment did not reduce total leafy spurge stem densities. Defoliation twice in a growing season for 4 consecutive year reduced total leafy spurge stem densities by 55% over non-defoliated controls. However, cattle use would likely be limited in these treatments due to the high density of leafy spurge stems.

Reduced-tillage practices have allowed leafy spurge to fest cropland. The reduction in leafy spurge infestation and winter-hardiness by fall tillage, or herbicide treatment was evaluated (Lay and Messersmith, 1993). Cultivation reduced the leafy spurge root system faster than herbicide treatment especially at the 15- to 30 cm depth, and cultivating leafy spurge twice each fall for 3 years provided compete control.

Several grasses are competitive with leafy spurge including 'Rebound' smooth brome, 'Rodan' western wheatgrass, 'Pryor' slender wheatgrass, and 'Manska' pubescent wheatgrass. Cultivating twice each fall after harvest for three years in cropland completely control leafy spurge. A successful long-term management program should be designed for species situation and should include combinations of herbicides, insects, grazing, and/or seeding competitive species (Lym, 1998). Another test with twelve grass genotypes from North Dakota shows that the 'Rebound' smooth brome, 'Rodan' western wheatgrass, 'Bozoisky' Russian wildrye, and 'Arthur' Dahurian wildrye with better results (Lym and Tober, 1998), and they reduced leafy spurge stem density an average of 63% after 3 years in a silty clay soil at Fargo. 'Reliant' intermediate wheatgrass reduced leafy spurge stem density every year for 3 years, including an 85% reduction the second year after planting, and consistently produced high herbage yields. 'Rebound' and 'Reliant' intermediate wheatgrass averaged 72% leafy spurge reduction 3 years after seedling in a loamy sand soil at Jamestown. 'Reliant' intermediate wheatgrass and 'Manska' pubescent wheatgrass provided the most consistent herbage production，which averaged about 2 000 kg/hm^2 annually for 3 years.

Biological Control

Biological control of weeds is the deliberate use of natural enemies to reduce the density of a target weed to below an economic threshold. In classical biological control one or more organisms，usually insects or pathogens，from another part of the world are established on the weed (Harris *et al.*，1985). The testing represents is very expensive，especially in the initial stage. However，it contrast to other methods of weed control，once the agent is established and distributed，there is little or no continuing cost. The conflict of interest should be considered and evaluated first，even tested，before any biological agent is cleared and released. So far，the list of non-American insects that attach leafy spurge includes 131 species have been collected，and about three-fourths of them that feed on restricted to the genus of leafy spurge，including *Aphthona* spp. (Coleoptera：Chrysomelidae). The prospects are excellent that biological control can reduce the aggressiveness of the weed on these sites by establishing spurge insects and pathogens from Europe and Asia.

Efforts to manage leafy spurge with biological control begin in 1960s. And first leafy spurge bio-control agent in U. S. (the Hyles hawk moth) is released in 1964. In 1978，Entomologists initiate a search for host-specific *Aphthona* spp. in Europe. The search identifies four flea beetles：*A. cyparissiae*，*czwalinae*，*flava* and *nigriscutus* for further study；all are ultimately imported and released. In 1985，first flea beetle (*A. flava*) released. In 1988，USDA-APHIS begins leafy spurge biological control program. In 1989，*A. nigriscutis* was approved and released，and *A. lacertosa* was approved and released in 1993.

Following bio-controls are detailed in this review：

Pathogen：Fungi and others

Fungi recorded on *Euphorbia* species has a lot，but very little effort has been directed toward their use (Harris *et al.*，1985). The comparison of methods for selecting fungi pathogenic to leafy spurge was reviewed (Yang *et al.*，1991).

The host range of *Myrothecium errucaria* (Hypocreales：Incertae sedis) isolated from leafy spurge collected from China，has potential as a mycoherbicide against annual herb (Yang，1995). Leafy spurge inoculated with *Myrothecium verrucaria* had dead tops or shoots with blackened stems and blackened，curled，or wilted leaves (Yang and Jong，1995). *Myrothecium verrucaria* did not spread from diseased plants to healthy plants，even when the healthy plants touched the diseased plants in the dew tent for 7 days. Four week old or younger seedlings of leafy spurge grown from seeds were killed with one inoculation，but repeated inoculations were required to kill older plants. Pathogenicity tests on 89 collections of nine species of *Euphorbia* and on reed canarygrass (*Phalaris arundinacea*) showed that the pathogen severely infected all collections tested.

Six multinucleate and two binucleate strains of *Rhizoctonia* spp. pathogenic to the weed leafy spurge were compared in aggressiveness (Caesar *et al.*，1993；Caeser，1994). Pathogenicity was tested by inoculating stems of leafy spurge or planting roots or seeds in soil infested with *Rhizoctonia* strains. The results indicate variation in aggressiveness to leafy spurge and in host range among strains of *Rhizoctonia* spp. from which optimum bio-control strains may be selected for appropriate use. R230，an isolate of *Rhizoctonia solani anastomosis* group 5 from leafy spurge，caused root and crown rots on leafy spurge when inoculated via soil in greenhouse experiments (Yuen and Masers，1995). *Rhizobacteria* have been shown to be phytotoxic to leafy spurge in laboratory assays. The field shows that *Pseud-*

omanas fluorescens , deleterious rhozobacteria, could reduce root weight and root carbohydrate content by 20% from test in North Dakota (Brinkman *et al.*, 1999). To evaluate the potential of *Rhizobacteria* as bio-control agent, the cell cultures and callus tissues of leafy spurge were tested (Souissi and Kremer, 1994). A rapid microplate callus bioassay for assessment of rhizobacteria for bio-control of leafy spurge has been reported (Souissi and Kremer, 1998). Its root colonization of seedlings by rhizobacteria is also reported (Souissi *et al.*, 1997a). And interaction of rhizobacteria with leafy spurge callus tissue cells is also reported (Souissi *et al.*, 1997b). It is concluded that callus tissue may provide an excellent working model to investigate the mode and/or mechanism of action of potential bio-control agents on their host plants.

Leafy spurge stands in the Prairie Provinces in Canada were surveyed for plant pathogens during the growing seasons of 1981, 1982 and 1983 (Mortensen, 1984). In most sites surveyed, leafy spurge was disease-free. The most frequent diseases observed were leaf spot and top dieback caused by *Alternaria* spp. (Dothideomycetes: Pleosporales), and a leaf spot caused by *Septoria guepini* (Mycosphaerellaceae). A potential agent, *A. tenuissima* was obtained from diseased plant of the leafy spurge (Krupinsky and Lorenz, 1983), and the experiments for *A. anguistiovoidea* were also made (Yang *et al.*, 1990). Several fungi were isolated of which *Fusarium* spp. (Sordariomycetes: Hypocreales) were the most frequent. Strains of *Fusarium* spp. causing root disease and crown rot on leafy spurge in natural epidemics and in association with stand declines were identified as *F. oxysporum*, *F. solani*, and *F. proliferate*. These species predominated among *Fusarium* spp. isolated from stunted and diseased feeder roots and crowns. The result indicates that *Fusarium* spp. capable of causing disease on leafy spurge vary as to species, virulence, and compatibility group and are found in a number of sites where this troublesome perennial weed occurs (Caesar, 1996). Further studies on the host range were conducted in greenhouse using both European and US strains of *Fusarium* spp. pathogenic to *Euphorbia* spp. (Caesar *et al.*, 1999).

Previous field investigations revealed pathogen-insect interactions on the roots of leafy spurge leasing to mortality. The study shows that the most effective condition for inducing disease and subsequent mortality of leafy spurge includes a synergism between plant-associated microorganisms and root-damaging insects (Kremer *et al.*, 2006). Furthermore, the results are valuable for identifying sites for collecting soil-borne microorganisms on weeds in their native range for evaluation as bio-control agents in their invasive range.

Insects Control

Gassmann and Schroeder (1995) reviewed the history and lessens from leafy spurge and allied species in searching the biological agents in Europe in the past 40 years with solid comments and results. More insect species were found on the most common and the geographically most widespread spurge species and on those occurring in a wide range of habitat types. The insect families most frequently associated with perennial spurges in Europe are the chrysomelids, sesiids, cecidomyids and anthomyiids.

Biology, ecology, and host specificity of five *Aphthona* species from Europe has been studied, and all of them are univoltine and overwinter as larvae (Gassmann *et al.*, 1996). The host range of these species is restricted to species in the subgenus *Esula*. Few than 19 of 113 *Euphorbia* species native to the US appear to be potential host plans for *A. flava*. Release of *A. flava* were made in Montana (1985—1987), North Dakota (1985) and Idaho (1986). The potential host plant range of the European flea beetle, *A. flava*, a candidate biological control agent for leafy spurge was also evaluated (Pemberton and Rees, 1990). *A. chinchihi* Chen was collected in China feeding on leafy spurge, and studies were conducted on its host specificity in the laboratory, using field collected adults and their progeny (Fornasari, 1997). This species can effectively complement the impact of the other natural enemies of leafy spurge established from Europe in the USA and Canada. The adults feed on leaves and shoots and the larvae, which cause the main damage to the plant, feed on the hypogenous portion of the plant, seriously stressing the plant and preventing its vegetative spread. The experiments demonstrated that it has a high level of specificity. This flea beetle completed its life cycle only on leafy spurge. Also, because of its ecological valence, *A. chinchihi* has a very good potential as a bio-control agent in North America. The black dot flea beetle, *A. nigriscutis* , is very effective in control leafy spurge from the Great Plain in North America (Mico and Shay, 2002). In Canada, the introduced population of *A. nigriscutis* increased significantly in 1994 and 1995, but not enough to damage the host-plant (Lesage, 1996). Phenology models for first emergence of adult *A. nigriscutis* is also reported (Legg *et al.*, 2002).

Acroclita subsequana (Lepidoptera: Tortricidae) a possible agent for biological control of leafy spurge in North America is also reported (Sobhian, 1996). The new description of *Chamaesphecia* spp. (Lepidoptera: Sesiidae) recently from Europe may be another source for the biological control on leafy spurge in North America because its larvae have could feed and develop in the roots of leafy spurge (Tosevski *et al.*, 1996). The beetle *Thamnurgus euphorbiae* (Coleoptera: Scolytidae), whose larvae feed in the inner stems of *E. characias* found in Italy, was selected as a candidate agent for the biological control of *E. esula-virgata* in the USA. Its adaptation to and survival on several *E. esula-virgata* ecotypes from North America justified host range studies conducted in Italy during 1993 —2001 (Campobasso *et al.*, 2004a, b). Bionomical and host-range studies of the lacebug, *Oncochilia simplex* (Hemiptera: Tinigidae) were made in laboratories (Pecora *et al.*, 1992), and the authors conclude that *O. simplex* should be introduced as a biological control agent against leafy spurge in the United States. The anthomyiid fly, *Pegomya courticornis* (Diptera: Anthomyiidae), introduced into Alberta from Europe, normally induces simple galls on subterranean stems (Gassmann and Shorthouse, 1991; Shorthouse and Gassmann, 1994). However, it has been found on horizontal roots of spurges. Tissues of the root galls were composed of gall parenchyma that had proliferated from feeding sites near the outside edge of secondary xylem. It is assumed that some larvae inadvertently tunnel beyond the base of stems into the roots and that similar galls will form on spurges. *Dasineura* sp. near *capsulae* (Diptera, Cecidomyiidae) was also introduced as a candidate for biological control of leafy spurge complex in North America since the restricted host range on leafy spurges (Pecora *et al.*, 1989). Studies of a population of this midge associated with leafy spurge indicates that this midge is univoltine, and completed development only on the test plants on which it oviposited, all in the subgenus *Esula* .

Since 1988, the USDA, PPQ (Plant Protection and Quarantine), APHIS (Animal and Plant Health Inspection Service) has coordinated a classical biological control implementation program against leafy spurge in the USA (Hansen *et al.*, 1997). Through this program nine Eurasian insect species have been imported and released in the USA, including six species of flea beetles, *Aphthonia* spp. , a root-boring moth, *Chamaesphecia hungarica* (Lepidoptera: Sesiidae), a root-boring beetle, *Oberea erythrocephala* (Coleoptera: Cerambycidae), and a gall midge, *Spurgia esulae* (Diptera: Cecidomyiidae). These species have been released in 188 counties in 19 states. Established populations of at least one agent are present in 148 counties in 18 states, while populations of at least one agent in 62 counties in 16 states are large enough to permit collection and distribution to other leafy spurge-infected areas. Biological control agents have been released throughout areas of the United States infected by leafy spurge. *S. capitigena*, a kind of insect from Europe, was also used to control leafy spurge in North America (Lloyd *et al.*, 2005a, b; Sobhian *et al.*, 2000). Another species, *S. esulae* from Italy, also introduced based on the studies since early 1980s, has been released in 1985 (Pecora *et al.*, 1991).

Nonlinear models were used to estimate first emergence and peak abundance dates for *A. lacertosa* and *A. nigriscutis* (Skinner *et al.*, 2006). 26 field sites were sampled for flea beetle abundance at weekly intervals for eight weeks in three western Minnesota counties in 2000, 2001, and 2002. A three-papameter Weibull function, fit to observe cumulative probability distributions, were used to predict accumulated degree-days to first emergence. Models were validated with additional data sets from Minnesota, Montana, and North Dakota. Estimated date of peak emergence provided useful predictions of peak emergence for Minnesota and North Dakota, but failed to predict peak emergence in Montana. The variation in climate and environmental conditions between Midwestern states and Montana were responsible for differing emergence patterns. The phenology models should be developed regionally to provide useful predictions of peak emergence for land managers.

Since 1993, *A. abdominalis* was collected from Italy as a candidate for biological control of leafy spurge in North America (Fornasari, 1995). The studies were conducted to determine the host specificity of *A. abdominalis* both in the field and in the laboratory, using field-collected adults and their overwintering progeny (Fornasari and Pecora, 1995). *A. abdominalis* has four or more generations per year in Italy and occupies a well-defined ecological niche on leafy spurge. The main damage by this agent is caused by the larvae feeding on the roots and the underground portions of shoots throughout the generations of this multivoltine flea beetle. Tests with larvae and adults, conducted in the laboratory and in the field, under no-choice and free-choice conditions, demonstrated that this flea beetle has a high level of specificity. In the field, under free choice conditions, it attached and developed only on leafy spurge. This flea beetle has a good potential for being effective in humid habitats, where other flea beetles previously released did not perform well. The effect of temperature on embryonic development of flea beetle, *A. abdominais*, was studied (Fornasari, 1995). The experimental data gave a developmental zero between 12 and 13 degree C. The embryos completed their development at constant temperatures from 15 to 38 degree C. Development required from 32.6 days at 15 degree C to only 4 days at 35 degree C constant temperatures. The life history and host specificity of *A. venustula* has been fully studied and reported (Gassmann, 1996).

Taxonomy, distribution, life history and host plant relationships of the cerambycid *Oberea erythrocephala* (Coleoptera: Cerambycidae), an oliphagous, univoltine stem- and root-miner of *Euphorbia* spp. are discussed (Schroeder, 1980). The results of feeding and oviposition tests with 43 plant species in 20 families, and of larval transfer tests with 31 plant species are presented, and show that *O. erythrocephala* is restricted to certain species of the genus *Euphorbia*, not including the ornamental species *E. pulcherrima* and *E. milii*. In Europe the beetle is widely distributed and locally quite destructive. It accepts the target weed, leafy spurge, and develops normally on it and therefore should be relatively easy to establish in the field. The beetle

O. erythrocephala was introduced into Oregon, Montana, and Wyoming between 1980 and 1984 (Rees *et al.*, 1986). Although it was not recovered in Oregon and Wyoming, it became established at two of three release site in Montana and appears to be accepting leafy spurge plants at a fourth.

The effect of temperature on developmental rates of over-wintered third instars to adult for *A. laceratosa* and *A. nigriscutis* were made (Skinner *et al.*, 2004), and the result shows that the different climatic and environmental conditions may have played a role. In Yugoslavia, the Entomofauna of leafy spurge was surveyed between from 1985 to 1988, and over 32 insect species were found but not fully studied yet (Zlof *et al.*, 1989). Black (*A. lacertosa* and *A. czwalinae*; Kalischuk *et al.*, 2004) and brown (*A. nigriscutis*) flea beetles are among the more successful biological control agents used in the control and management of leafy spurge on a relatively large scale in the Northern Great Plains. The detail and full report to document the population dynamics in response to control by black and brown flea beetles, to determine the role of selected site characteristics on establishment and persistence of the beetles, and evaluate the general response of the resident vegetation to control leafy spurge have been reported (Butler *et al.*, 2006). In late June 1998, about 3 000 insects of each species were released into permanently marked plots in northwestern South Dakota and southeastern Montana. Beetle abundance, density and foliar cover of leafy spurge, and foliar cover of the resident vegetation were evaluated each year from 1998 through 2004. Black beetles increased rapidly and peaked at 65% of their measurable potential abundance within 2 years following release and dominated all release plots throughout the study. Although population growth characteristics of black flea beetles were highly variable, the successful patterns in reducing the dominance of leafy spurge were fairly consistent. By 2004, foliar cover of leafy spurge on both released and non-release plot was significantly reduced compared to pre-release values. Foliar cover of grass and grass-like plants increased concomitantly with the reduction in leafy spurge dominance while cover of forbs on release and non-release plots remained consistently below non-infested values. The temporal dynamics in large natural area with biological control of leafy spurge by flea beetles has been evaluated in Theodore Roosevelt National Park, western North Dakota (Larson *et al.*, 2004). *A. lacertosa* and *A. nigriscutis* have been released at more than 1800 points in the 18 600 hm^2 South Unit of the park beginning in 1989; most releases have occurred since 1994. The permanent vegetation plots throughout the infested area of the park and determine stem counts and biomass of leafy spurge and abundance of the two flea beetle species at these plots each year from 1999 to 2001. Both biomass and stem counts declined over the 3 years of the study. Both species of flea beetle are well established within the park, and have expanded into areas where they were not released.

The biology and host specificity of *Nephopterix divisella* (Lepidoptera: Pyralidae) was studied to evaluate its potential as a new biological control agent (Cristofaro *et al.*, 1998). The use of agromyzid flies (Diptera: Agromyzidae) to control leafy spurge in North America and prospects is also reported (Martinez and Sobhian, 1998). Effect of leafy spurge on growth and mortality of migratory grasshopper nymphs (Orthoptera: Caelifera) are also reported (Roberts and Olson, 1999a).

Refining the process of selecting specialist herbivores that are used as biological control agents to maximize effects on the targets can diminish the risk to non-target species. While abiotic factors (e. g. plant demography and agent host interactions) have been explored for clues to improve the way we make agent selection decisions, recent ecological research indicates that biotic factors related to the habitat (e. g. plant and soil nutrient compositions, and soil characteristics) are important predictors of insect herbivore community composition (Schwab and Raghu, 2006).

Other works in insect control part are not very positive. The feasibility of using the spurge hawkmoth, *Hyles euphorbiae* (Lepidoptera: Sphingidae), as a biological control agent was evaluated in Nebraska (Forwood and McCarty, 1980), but the results show that the spurge hawkmoth will not become a valuable biological control agent for leafy spurge (Rees and Fay, 1989). The two European root-boring moths, *Chamaesphecia hungarica* and *Ch. astatiformis*, two candidates for the biological control of leafy spurge in North America was tested (Gassmann and Tosevski, 1994). Both, univoltine and overwinter as mature larvae, have a lower survival rate on leafy spurge than on their field hosts, and thus are not optimal candidates for the biological control. However, the rate of larval development and larval growth on the target weed and on the tow field hosts is nearly the same. The biology and host specificity of *Oxicesta geographica* (Lepidoptera: Noctuidae) from Romania, Hungary and Southwestern Russian were also studied to evaluate the potential biocontrol agent (Cristofaro *et al.*, 1994). The results of no-choice feeding tests with first instars on 93 plant species and biotypes, distributed in 33 families, show that *O. geographica* completed its life cycle mainly on plants of *Euphorbia*, subgenus *Esula*, and occasionally fed and developed on species in other subgenera of the genus. And studies of late instars did not show any important extensions of the host range.

Chemical Control

The history and progress to control leafy spurge in chemicals can be traced from the early research in the United States in 1930s (Bakker, 1937; Alley and Messersmith, 1985), and in Canada in 1940s (Best *et al.*, 1980). Since then, different kinds of productions have been tested and applied in control of leafy spurges. In addition, chemical control of leafy spurge is abased on the nature of the infestation, because the methods suggested and the herbicides that can be used in range and pastureland, non-cropped areas and cropped areas differ considerably: range and pastureland (such as picloram), cropland (such as 2,4-D), non-cropland (include utility, highway, pipeline and railroad rights-of-way, industrial sites, fence row and around farm buildings, with combinations).

Imazapic applied with a methylated seed oil adjuvant tended to provide greater leafy spurge control than when applied with other types of adjuvants (Markle and Lym, 2001). The absorption and fate of imazapyr in leafy spurge is also reported (Nissen *et al.*, 1995). And result shows that Imazapyr phototoxicity to leafy spurge appears to result from high imazapyr absorption, translocation to underground meristematic areas (root and adventitious shoots buds), and a slow rate of metabolism.

Field research was conducted to determine the most effective quinclorac treatment for leafy spurge control (Kuehl and Lym, 1997). Quinclorac applied with the crop-oil-based adjuvant Scoil provided similar leafy spurge control compared to quinclorac applied alone. Quinclorac plus Scoil applied with picloram provided better leafy spurge control than quinclorac plus Scoil alone. Quinclorac absorption, translocation, metabolism, and taxicity in leafy spurge were also evaluated for the suitability of this herbicide for use in the control of leafy spurge (Lamoureux and Rusness, 1995).

The test with imidazolinone and sulfonylurea were tested in the fall on rangeland sites near Ainsworth and Columbus, Nebraska (Stougaard *et al.*, 1994). Imidazolinone and sulfonylurea herbicide combinations did not improve leafy spurge control nor affect forage grass yields when compared with herbicides applied alone. Imazapyr and sulfometuron were the most efficacious, providing greater than 80% leafy spurge control 9 months after treatment. Imazethapyr provided 80% control of leafy spurge 9 months after treatment when applied to a coarse textured, low organic matter soil. In contrast, leafy spurge control was on 15% when imazethapyr was applied to a fine textured soil. Chlorsulfuron did not control leafy spurge, regardless of site characteristics. And imazapyr reduced perennial grass yields by more than 60%.

Leafy spurge viable seed production and germination were reduced by 2, 4-D applied during flower development and seed formation, in the field (Al-Fenaid *et al.*, 1993). The viable seed production was reduced when 2, 4-D was applied at all growth stages after the start of flower bud development. Leafy spurge seed germination was higher in gibberellic acid than in water for seed collected from untreated plants and from plants treated with 2, 4-D 7, 14 and 21 days after bud initiation. This research shows that 2, 4-D must be applied prior to flower bud development to prevent seed production. Annual application of picloram and picloram plus 2, 4-D and biannual application of 2, 4-D for 5 consecutive years was evaluated for leafy spurge control (Lym and Messersmith, 1987). The laboratory experiments for adjuvant effects on imazethapry, 2, 4-D and picloram absorption by eafy spurge was also carried (Thompson *et al.*, 1996). The absorption, translocation, and metabolism of 14C-picloram and 14C-2, 4-D applied alone and together to leafy spurge was also evaluated (Lym and Moxness, 1989) which show it will increased leafy spurge control when these herbicides are applied together. The relative humidity after application, spray additives, and solution pH affected both foliar absorption and translocation of 14C-picloram to leafy spurge roots (Moxness and Lym, 1989). The absorption, translocation, root release, and metabolism of imazethapyr by leafy spurge were determined under growth chamber condition (Nissen *et al.*, 1994). The picloram metabolism was studied in rooted cuttings and excised leaves of leafy spurge (Frear *et al.*, 1989). And various chemical controls at different places in different dose and different conditions to leafy spurge as well as the evaluations have been tested and carried in different area among northwest North America (Hein and Miller, 1991; Lym, 1992a, b; Regimbal and Martin, 1984, Masters *et al.*, 1994, 1998; Thompson and Nissen, 1998), including to determine cost effective (Lym and Messersmith, 1985a, 1990b; Moomaw and Martin, 1990), and some even established with model to determine the best control of leafy spurge (Lingle and Suttle, 1985).

Response of leafy spurge clones to chlorsulfuron, clopyralid, and glyphosate were also reported (Frank and Tworkoski, 1994). Clones of leafy spurge varied significantly for all responses to each herbicide. The differential effects of chlorsulfuron, glyphosate, and clopyralid on leafy spurge suggest that genetically based differences may account for the failure of the herbicides to kill all plants within collection locations or between collection locations. The influence of glyphosate on bud dormancy also reported (Maxwell *et al.*, 1987).

Efficacy and economics of leafy spurge control in pasture with various chemicals were studied (Gylling and Arnold, 1985). Several treatments resulted in leafy spurge control exceeding 90% mean herbage dry-weight yield in treated plots was 2 340 kg/hm^2, a 67% increase over untreated plots. Marginal net return over marginal cost from herbicide treatments ranged from \$35 to \$63/hm^2. Treatments providing satisfactory leafy spurge control with minimum economic risk were annual spring applications of 2, 4-D at 1.7 kg/hm^2 or dicamba +2, 4-D at 0.6+1.1 kg/hm^2 and the biannual application of 2, 4-

D at 0. 8 kg/hm^2.

Leafy spurge control and forage production after various fall-applied herbicide treatment rotations were evaluated in a bluegrass pasture and a mixed grass prairie (Lym and Messersmith, 1985c, 1994). Leafy spurge control with four herbicides was evaluated at nine sites in six Great Plains States, and the results show that sulfometuron alone did not control leafy spurge satisfactorily 12 month after treatment (Beck *et al.*, 1993).

The chemical control in North Dakota from 1963 to 1982 was reviewed in twenty years (Lym and Messersmith, 1985b). The temperature changes prior to picloram application affect its activity in leafy spurge (Lym and Messersmith, 1990a). Diflufenzopyr is also a kind of useful chemicals effectively to control of leafy spurge (Lym and Deibert, 2005).

Grazing Control

Grazing experiment to control leafy spurge was also started in 1930s with sheep (Bakke, 1937). Use of Angora goats is another tool available to land managers to manage leafy spurge infestations in the Northern Plains (Kirby *et al.*, 1997). Angora goats have been suggested as biological control agents for leafy spurge, especially in environmentally sensitive or limited access areas. Dietary preferences and dietary nutritive content of herded Angora goats were evaluated over a two-year period in North Dakota. Relative preferences of forages were evaluated by comparing botanical composition of diets as determined by microhistological analysis of fecal samples to forage availability in the field. Leafy spurge and shrubs comprised the largest percentage of goat diets throughout each grazing season. Goats preferred leafy spurge and shrubs at all the times and avoided most cool-season grass species. The nutritional requirements of Angora goats nursing kids were met throughout the grazing season.

The germinability and viability of leafy spurge seeds following ingestion by sheep and goats were evaluated (Lacey *et al.*, 1992). The results indicate that sheep and goats are effective biological tools for reducing spread of leafy spurge seeds (Landgraf *et al.*, 1984; Olson and Wallander, 1998; Olson *et al.*, 1996), but not final tool to erased from root (Masters, 2003).

Comprehensive Control:

No single agent or herbicide could control such kind of aggressive invasive plant, and various treatment and combination will great increase the effect in controlling spread and density, and finally removed it.

Integrated Pest Management (IPM), a desirable approach to the selection, integration, and use of (pest control) methods on the basis of their anticipated economic, ecological, and sociological consequences has been formed since 1980s (Allen and Bath, 1980; Watson, 1985). IPM for leafy spurge has been evaluated as invasive plant as Theodore Roosevelt National Park, North Dakota (Larson *et al.*, 2007). The effects of herbicides on leafy spurge abundance and on dynamics of flea beetles (*Aphthona* spp.) used to control leafy spurge were evaluated over three field seasons following herbicide application. The result suggests that the most effective component of IPM for leafy spurge at the experience site is biological control, and all herbicide effects were short-lived.

The combination of flea beetles and herbicide can increase leafy spurge control when compared with either methods used alone (Lym, 1998; Lym and Nelson, 2002; Nelson and Lym, 2003). The combination treatment was most successful when used with established flea beetles populations, which could save the expensive from 30—50 percent with the combination treatment compared with herbicides alone. Dicamba, 2, 4-D, glyphosate, and picloram have commonly been used to control leafy spurge (Lym, 1989). Ten insect species for leafy spurge have been released in North Dakota, and the most successful have been the flea beetles, *A. nigriscutis*, *A. czwalinae*, and *A. lacertosa*. The leafy spurge gall midge (*Spurgia esulae*) has been most successful near wooded areas. Herbicides combined with either the leafy spurge flea beetles or gall midge has controlled leafy spurge better than either method used alone. Grazing with sheep or goats is a cost-effective method for controlling leafy spurge top growth in large infestations. The grazing combined with fall-applied picloram plus 2, 4-D reduced leafy spurge density more rapidly and maintained control longer than either method used alone (Lym, 1998).

Biological control is an alternative to chemical control for leafy spurge, especially along railroad right-of-ways (Lym and Nelson, 2000). Re-vegetating leafy spurge infected rangeland with native tallgrass was also conducted (Masters and Nissen, 1998). The four experiments were conducted with imazapyr, sulfometuron and in combination by glyphosate to apply to leafy spurge at different doses and different seasons. Leafy spurge yields were usually reduced in areas where tallgrass yields were greatest. Another test was carried in Crook County, Wyoming, to determine the potential of eleven grass species to compete with leafy spurge as an alternative to repetitive herbicide treatments, and the result shows that 'Bozoisky' Russian wildrye and 'Luna' pubescent wheatgrass are the most promise for successful competition (Ferrell *et al.*, 1998).

An invasive weed can occupy a variety of environments and ecological niches and generally no single control method can be sued across all areas the weed is found (Lym, 2006). Biological control agents integrated with other methods can increase and/or improve site-specific weed control, but such combinatorial approaches have not been widely utilized. The successful leafy spurge control program provides examples for future integrated weed programs that utilize biological control agents with traditional methods. Weed control methods can be used separately, such as when the leafy spurge gall midge (*Spurgia esulae*) reduced seed production in wooded areas while herbicides prevented further spread outside the tree line. Traditional methods also can be used directly with biological control agents. Incorporation of *Aphthona* spp. with herbicides has resulted in more rapid and complete control than either method used alone. Also, the insect population often increased rapidly following herbicide treatment, especially in areas where *Aphthona* spp. were established for several years but had been ineffective. Incorporation of *Ahthona* spp. with sheep or goats grazing has resulted in a large decline in leafy spurge production than insects alone and in weed density than grazing alone. Controlled burns can aid establishment of biological control agents in marginally suitable environments, but timing of the fire must be coordinated to the insect's life-cycle to ensure survival. Integration of biological control agents with re-vegetation programs required the agent to be the last method introduced because the cultivation and herbicide treatments necessary to establish desirable grasses and forbs were destructive to the insect.

Prospects and Summary

Survey

With spread of leafy spurge and awareness in North America, the survey of current infection area has becoming a huge challenge, especially for those remote areas where common method can't be accessed for human beings. Use of remote sensing for detecting and mapping leafy spurge has revealed broad prospect to monitor the spread or decline of leafy spurge recently (Everitt *et al.*, 1995), which could be used for constructing distribution and abundance maps with satellite hyperspectral data for larger regional areas (Williams and Hunt, 2003). Hyperspectral data processing for repeat detection of small infestations was also reported (Glenn *et al.*, 2005). Plant canopy reflectance measurements showed that leafy spurge had higher visible (0.63—0.69 mu/m) reflectance than several associated plant species. The conspicuous yellow bracts of leafy spurge gave it distinct yellow-green and pink images on conversional color and color-infrared aerial photographs, respectively. Leafy spurge also could be distinguished on conventional color video imagery where it had a golden yellow image response. Quantitative data obtained from digitized video images showed that leafy spurge had statistically different digital values from those of associated vegetation and soil. Computer analyses of video images showed that light reflected from leafy spurge populations could be quantified from associated vegetation. The image analysis to separate leafy spurge from other plant species and objects is also reported (Birdsall *et al.*, 1997). The spectral characteristics of leafy spurge is fully discussed with detail (Hunt *et al.*, 2004), and the special characteristics are important for constructing a well-documented spectral library that could be used with hyperspectral remote sensing (Hunt *et al.*, 2004).

Classical monitoring techniques, which often involve extensive ground survey efforts, can't be aided by the synoptic nature of remotely sensed imagery. The research addresses the use of Space Imaging's 4-m multispectral Ikonos imagery for the survey and detection of leafy spurge infestations (Casady *et al.*, 2005). Survey data were collected at a site in western North Dakota and used to produce supervised classifications of leafy spurge infestations with Ikonos imagery. Finally, individual patches of leafy spurge were analyzed to determine the minimum patch size and percent cover that were detectable with supervised classification of Ikonos imagery. Multi-date imagery provided increased accuracy, but improvement was not consistently significant. Leafy spurge infestations of ＜30％ cover and 200 sq. m were not reliably detected.

Management

Weed population models can serve as a framework to organize weed biology information and to develop weed control strategies. Models help to identify information gaps, to set research priorities, to develop hypotheses pertinent to weed population regulation, and to suggest control strategies (Maxwell *et al.*, 1988). A population simulation model of leafy spurge was used to demonstrate the applicability of population models to weed science. Sensitivity analysis of an existing leafy model indicated that transition from basal buds to vegetative shoots, survival of vegetative shoots, and survival of basal buds over winter were important transition parameters influencing population growth of this weed species. Four control strategies were simulated and were compared to field studies to show the predictive and management potential of the modeling approach.

The Ecological Areawide Management (TEAM) of leafy spurge program was developed to focus research and control efforts on a single weed, and demonstrate the effectiveness of a coordinated, biologically based, IPM (Anderson *et al.*, 2003). This was accomplished through partnerships and teamwork that clearly demonstrated the advantages of the biologically based IPM approach. However, the success of regional weed control programs horizontally across several states and provinces also requires a vertical integration of several sectors of society. Awareness and education are the essential elements of vertical integration. Therefore, a substantial effort was made to produce a wide variety of information products specifically designed to educate different segments of society. The land managers and agency decision markers have seen the potential of using the TEAM approach to accelerate the regional control of leafy spurge. The example set by the TEAM organization and participants is viewed as a model for future weed-control efforts. The survey to evaluate respondent′s perspectives of managerial, institutional, and social factors from local ranchers, decision makers and public land managers in North and South Dakota, Montana and Wyoming shows that the financial constraints may be addressed through cost-share programs either offered locally or through state agencies, and it is followed by a lack of knowledge to work with various controls (Sell *et al.*, 1999), even fire control (Masters, 2003).

Proposal for TEAM Leafy Spurge area-wide program submitted in 1996, and TEAM Leafy Spurge is selected as the USDA-ARS′s first area-wide IPM program. The USDA-APHIS is named as a co-manager of the 5-year program with ＄4.5 m from 1997, and officially finished in 2002. TEAM Leafy Spurge publishes the "*Biological Control of Leafy Spurge*" handbook. More than 14 000 copies are distributed to end users in 16 states and several Canadian provinces during its first six weeks of publication. In 2001, TEAM Leafy Spurge is featured on the BBC′s "Earth Report", a documentary-style environmental news program. The episode, "Alien Invaders", is broadcast in 220 countries to a possible audience of 167 million viewers. Distribution of the TEAM Leafy Spurge "Biological Control of Leafy Spurge" handbook hits 30 000. "IPM Information Series/Biological Control of Leafy Spurge CD" includes a narrated PowerPoint presentation, the bio-control manual, catalogs of photos, informative profiles of bio-control agents, and miscellaneous resources. "Purge Spurge: Leafy Spurge Database" CD-ROM.

Leafy Spurge News, published by Agricultural Experiment Station, North Dakota State University Extension Service, North Dakota State University, Fargo, North Dakota, is semi-annual newsletter (basically) published since 1979, and it is also the best newsletter in North America regarding the single fight for leafy spurge in the world, but finally deceased in October 2005. Some of its contents from 1996 are available (http://www.team.ars.usda.gov/v2/publications/leafyspurgenews.html) with TEAM of ARS, USDA.

Molecular Approach

The molecular tool from biological field recently definitely opens a new field in controlling leafy spurge in the future. Even some tests and reports have been made, however, it is still a long way to go before the powerful way could be found and applied, especially in such largely infection area in North America.

The levels of inter- and intra-population genetic variation were determined in five North America populations of leafy spurge using chloroplast DNA (cpDNA) RELPs and RAPD markers (Rowe *et al.*, 1997), and the result shows that the high degree of genetic variability in North American leafy spurge suggests possible multiple introductions or a high degree of variability within leafy spurge populations in its native range. The genetic variation and relatedness among selections of North American and Eurasian leafy spurge was also made (Nissen *et al.*, 1992), and the result shows that the American accessions are closed related each other and to the Russian leafy spurge accession.

Effect of leafy spurge genotype on feeding damage and reproduction of *Aphthona* spp. is tested, and the genotype does affect feeding but not egg laying by *Aphthona* spp. adults (Lym and Carlson, 2002). However, the genotype affects gall midge (*Spurgia esulae*) establishment (Lym *et al.*, 1996), which was introduced in North Dakota (Lym and Carlson 1994).

Using molecular report showed (Horvath and Olson, 1998) that more than 16 genes have been identified, that are differentially expressed in underground buds of leafy spurge during dormancy break and growth initiation (Horvath and Anderson, 2002). A detailed expression analysis of these genes will allow them to be grouped by their responses to various signals known to play a role in control of underground bud growth. This information will be used to identify key cis-acting elements involved in the regulation of these genes, and such information on signal transduction processes may be used for developing new weed control strategies by the identification of novel target pathways and development of DNA-based herbicides. A genomic and near full length cDNA clone for a D-class cyclin gene from the leafy spurge has been isolated (Horvath *et al.*, 2005). Two subtractive cDNA libraries were developed to study genes associated with bud dormancy (reverse library) and initiation of shoot growth (forward library) in leafy spurge (Jia *et al.*, 2006). And the analysis of bud dormancy in the molecular method is also tested (Horvath *et al.*, 2002, 2005).

Workshop and Symposium

Since early 1980s, the fight to leafy spurge both locally and nationally have been largely began, and the various workshop and symposium were hold, and various kinds of publications and comprehensive serious monograph were also published. And among them, following should be not omitted here.

North Central Weed Control Conference Research Report published by North Central Weed Control Conference in 1980, with various publications, such as the variability of leaf spurge in the United States (37: 48—51). Leafy Spurge, Monograph Serious of the Weed Science Society of America, edited by Alan K. Watson (1985). Leafy Spurge Symposium Proceedings, Lincoln, Nebraska, July 22—24, 1994: Taxonomy and biology (4: 3—7). Proceedings: Leafy Spurge Strategic Planning Workshop, Dickinson, North Dakota, March 29—30, 1994. This publication include various review, such as biology (p. 57—62),

The coordinated regional research effort began with the Leafy Spurge Symposium, June 26 and 27, 1979, Bismarck, ND. About 125 educators, scientists, land managers, farmers, ranchers, legislators, and concerned citizens attended the symposium (Messersmith, 1989). One outcome of the plan was approved by the Great Plain Agricultural Council of a research committee, GPC-14 Leafy Spurge Control in the Great Plains, as a recognized organization to facilitate program coordination. The first GPC-14 meeting was held in June 1981, Fargo, and annual meetings have been since then: 1982 in Bozeman, MT, 1983 in Sundance, WY, 1984 in Dickinson, ND, 1985 in Bozeman, MT, 1986 in Riverton, WY, 1987 in Fargo, ND, 1988 in Rapid City, SD, 1989 in Bozeman MT, 1994 in Bozeman, MT, 1995 in Fargo, ND, 1996 in Brandon, Manitoba, 1997 in Gillette, WY, 1999 & 2001 in Medora, ND, and 2004 held at the Society for Range Management (SRM) 57th annual meeting January 24—30, 2004 in Salt Lake City, Utah.

What can leafy spurge teach us about management of noxious weed in general? Seven important lessons emerge (Cox, 1998): **1**) noxious weeds have been with us for decades, and there is time to develop successful and sustainable management strategies; **2**) a focus on eliminating the cause of weed problems is imperative, so that we create long-term solutions; **3**) biological control is a useful and cost-effective technique; **4**) management techniques need to include tools to reduce seed populations; **5**) encouragement of desirable vegetation is crucial; **6**) proper timing can maximize the effectiveness of non-chemical controls; and **7**) techniques must be appropriate for the treatment site.

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